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MODELING CONVECTIVE WATER FLOW IN REPACKED SAND COLUMNS BY BREAKTHROUGH CURVES OF CHLORIDE

S. ERŞAHİN[1,*] T. AŞKIN[2] C. TARAKÇIOĞLU[2] D.B. ÖZENÇ[2] K. KORKMAZ[2] T. KUTLU[3]

[1] Çankırı Karatekin University, Faculty of Forestry, Department of Forest Engineering, Çankırı, Turkey
[2] Ordu Univesity, Faculty of Agriculture, Department of Soil Science, Ordu, Turkey
[3] Kocaeli University, Vocational School of Aslanbey, Kocaeli, Turkey
***e-mail: ersahin@karatekin.edu.tr**

Abstract: This paper describes a novel theory for modeling water flow in porous media, such as soils, using breakthrough curves of nonreactive chemicals. Miscible displacement tests of chloride were conducted in repacked sand columns (30.0 cm length and 8.0 cm id.) that were prepared using washed sand particles with diameters of 2.0-1.0, 1.0-0.5, 0.5-0.25, and <0.25 mm. Sands with different particle-size were used to evaluate the theory in different water flow regimes. The resultant BTCs of Cl were used to model the hydraulic conductivity as a function of mobile water content ($K(\theta_m)$) of the sand columns. Laboratory measured and modeled values of saturated hydraulic conductivity (K_s) were compared to validate the model developed. Correlation analysis of the measured and approximated K_s values resulted in a correlation coefficient of r = 0.91 (P<0.001), suggesting that the model developed successfully utilized the data in BTCs to quantify the water flow in the sand columns evaluated in this study.

Key Words: Mobile water content, Hydraulic conductivity, Breakthrough curve, Chloride, Porous media, Water flow

1. INTRODUCTION

Water flow in a porous medium is a combined function of many variables and parameters inherent to the medium and fluid. The fluid properties are its viscosity and density, while pore geometry (size distribution of the pores, topology of pore space, and connectivity of the water phase) is the primary characteristic that defines the porous medium (Klute and Dirksen, 1986; Vogel and Roth, 1998). In natural porous systems, such as soils, the intricate nature of porosity makes it impossible to formulate the exact relationship between soil pore characteristics and hydraulic conductivity (Tuli, 2002).

Several methods have been developed to express hydraulic conductivity (K) in porous media as a function of porosity. For example, Henry Darcy first showed that water flux through sand filter beds was proportional to the gradient of the hydraulic head. This relationship, which is known as Darcy's law, has become one of the most important achievements in water flow theory. Indeed, numerous studies have since been conducted using analytical derivations of Darcy's equation (Gardner 1986; Stephens, 1996). One such equation is the Buckingham-Darcy Equation, which was developed in 1907, in which hydraulic conductivity is used instead of permeability and water pressure is replaced by matric head (Gardner, 1986).

J.L. Poiseuille and G.H.L. Hagen independently derived an equation for water flux in capillary tubes that was a function of the tube radius, pressure gradient, and viscosity of the fluid (Gardner, 1986). This equation, which is known as the Hagen-Poiseuille equation, is based on Newton's law of viscosity and has since been applied to flow through other cross sections. The Hagen-Poiseuille equation expresses the same relationship as the Darcy equation; however, the conductivity is given in terms of the measurable quantities of radius and viscosity in the Hagen-Poiseuille equation, adding meaning to the expression (Gardner, 1986).

Kozeny (1927) derived an equation to describe the relationship between water velocity and the properties of porous media. He assumed that pore space is composed of a bundle of capillary tubes with an average cross-sectional area. Later, Carman (1948, 1956) incorporated tourtousity effects into the Kozeny equation, resulting in the Kozeny-Carman equation. The Kozeny-Carman equation, which states that the permeability of a porous material is directly proportional to the cube of the porosity and inversely proportional to the square of soil particle surface area, is probably the best known and most often quoted equation relating porosity to permeability (Boersma et al., 1972).

Miscible displacement tests have long been used to evaluate the chemical transport properties of porous media (Nielsen and Biggar, 1961; Biggar and Nielsen, 1962; Nielsen and Biggar, 1962, 1963; van Genuchten and Wierenga, 1977; Ersahin et al., 2002; Kamra and Lennartz, 2005; and many others). In most of these studies, the shape of the breakthrough curve (BTC) was interpreted to assess features of the soil macropores and the extent of preferential flow, while the measured and fitted parameters of the BTC were used to quantitatively characterize the soils as transmitting media. In addition, a few of these studies attempted to characterize the pore water velocity variation quantitatively.

Many studies (Radulovich et al., 1989; Kung et al., 2005) of water and chemical breakthrough have been conducted in an attempt to characterize the pore size distribution and corresponding water flow characteristics of soil macropores. Such studies have used the functional relationship between the time needed for a tracer to travel through a soil column with a known length and the radii of pores through which the displacing solution flows. Deeks et al. (1999) used observed changes in solute concentration following miscible displacement of a 250 mg L^{-1} Cl solution to characterize the size-distribution of large soil conduits. In their study, they determined the values for the volume of discharging fluid in a specified time from the observed rate of movement of tracer within the soil to calculate the pore-radius using Poiseuille's equation.

The majority of miscible displacement studies have shown that one of the most important physical features of porous media is the magnitude of the volume of water not readily displaced, which is often termed the immobile water content of the porous system. Therefore, it has been suggested that the amount of mobile water needed to transport a given amount of a tracer within a specified time can be calculated. Using the approximated amounts of mobile water together with their corresponding arrival time in Darcy's equation can allow water flow to be modeled as a function of mobile water content in a system.Thus, this study was conducted to develop a theory to model water flow distribution in natural porous media, such as soils, as a function of mobile water content using displacement data for a nonreactive tracer. The theory and principles developed here were applied to the BTCs of chloride from small columns (30 cm length and 8 cm id) of uniform sand.

2. THEORETICAL

The capillary bundle model may be extended to develop a simple model of water flow in soils (Jury et al., 1991). The capillary bundle model is based on the idea that porous medium is composed of a number of capillary tubes with the same lengths, but different cross-sectional areas. The radius of the capillary bundle governs the rate of flow through the medium. In addition, it is assumed that all of the capillary tubes are continuous, with no dead ends or stagnant regions, although they may be twisted or tortuous. Finally, the model presumes that laminar flow prevails in each of the capillary tubes (Jury et al., 1991). The total flow of the porous medium is equal to the sum of the volume flow rates out of each tube divided by the cross-sectional area of the medium (i.e., soil column). The volume flow rate in a single capillary with a radius, r, is defined by Poiseuille's law (Jury et al. 1991; Deeks et al., 1999):

$$Q = \frac{\Pi r^4}{8\eta} \rho_w g \frac{\Delta H}{\Delta L}, \qquad (1)$$

where, Q is the flow rate ($L^3\ T^{-1}$), η is the coefficient of viscosity ($ML^{-3}T^{-1}$), ρ_w is the density of water (ML^{-3}), g is the acceleration due to gravity (LT^{-2}) and $\Delta H/\Delta L$ is the hydraulic gradient. The mean velocity over the cross-sectional area is (Hillel, 1980):

$$q = \frac{r^2}{8\eta} \frac{\Delta H}{\Delta L}. \qquad (2)$$

2.1. Relating the Capillary Bundle Model to a BTC

In the absence of longitudinal dispersion and diffusion of the tracer, such as in the case of piston flow, the resultant BTC will be identical to the one shown in Figure 1a. However, natural porous systems (e.g. soil) are composed of numerous capillaries, each having a particular size, shape, tourtousity, and connectivity to others. Additionally, the flow in a single capillary is not spatially uniform; rather, the highest velocities occur at the pore center and the slowest velocities occur in regions adjacent to the pore walls. Furthermore, the tracer has a tendency to move from areas with higher concentrations to those with lower concentrations via diffusion. These effects all result in the formation of a BTC similar to the one illustrated in the Figure 1b.

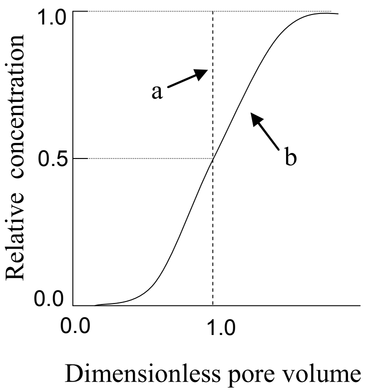

Figure 1. Hypothetical breakthrough curves for different displacement conditions a) piston flow and b) flow contributed by convection and hydrodynamic dispersion

When a nonreactive chemical is subjected to relatively rapid transport, the shape and location of the resultant BTCs are the outcome of the pore geometry (pore-size distribution, tortuosity, connectivity, shape, etc.) in a porous system. When compared to other components (shape, tortuosity, etc.) of the pore geometry, the pore-size distribution is the most important determinant of the shape of a BTC since the conductivity of an effective pore is largely dependent on its size. Assuming that the properties of convective transport are simply a function of pore-size, the BTC can be related to the size-distribution of the effective pores in the system. Supposing, for convenience, that the shape of a BTC of Cl is determined by the velocity distribution in the system, the following assumptions can be made:

In a miscible displacement test of a nonreactive chemical (i.e. chloride) conducted in a column repacked with an inert porous material (glass beads, washed sands, etc.), if the original solution at the inlet of the transmitting pores appears in the outlet of the column, the volume of effluent, ΔQ, needed to transport the mass of the chemical (tracer) between times t_i and t_{i+1} can be calculated as:

$$\Delta Q = \frac{\Delta M \Delta V}{M}. \qquad (3)$$

where, M is the concentration (in molar) of tracer at the inlet of the column (stock solution), ΔM is the difference in the concentration of the tracer at the outlet between times t_i and t_{i+1}, and ΔV (L^3) is the volume of effluent collected between t_i and t_{i+1}.

Applied to a BTC, the above formula gives Eq. (4);

$$\Delta P = \Delta C_r x \Delta P_r. \qquad (4)$$

where, ΔC_r is the change in relative concentration C_r ($C_r = C/C_0$), ΔP_r is the change in relative dimensionless pore volume ($P_r = V/P_0$, where V is the cumulative volume of effluent (L^3) and P_0 is the volume of water (L^3)) in the column determined by oven drying at 105 ^{o}C, and ΔP is the dimensionless pore volume needed to transport the mass of the tracer corresponding to ΔC_r. The value for ΔQ can then be calculated as:

$$\Delta Q = \Delta P x P_0 \qquad (5)$$

Knowing ΔQ allows us to calculate the hydraulic conductivity using Darcy's equation by:

$$K(C_{ri}) = \frac{\Delta Q_i}{\Delta A_i t_c} \frac{\Delta z}{\Delta H}, \qquad (6)$$

where, ΔA_i is the fraction of cross-sectional area of the soil column supporting the particular sized capillaries discharging ΔQ_i, t_c is the cumulative time that has elapsed since the beginning of the test, $\Delta z/\Delta H$ is the gradient of soil water head, which can be taken as unity for a miscible displacement test conducted under a pressure potential of zero. Hereafter, $\Delta z/\Delta H$ will be taken as unity, and, for brevity, will not be included in subsequent equations. The value for ΔA_i can be approximated by;

$$\frac{\Delta A_i}{A} = \frac{\Delta Q_i}{\Delta P_i x P_0}. \qquad (7)$$

Here it was presumed that the ratio of ΔQ_i to $\Delta P_{ri} x P_0$ was identical to the ratio of ΔA_i to A, where A is the cross sectional area of the column. Combining Eqs. (6) and (7) yields Eq. (8);

$$K(C_{ri}) = \frac{\Delta Q_i}{\frac{\Delta Q_i}{\Delta P_i x P_0} t_i}. \qquad (8)$$

2.2. Accounting for the Hydrodynamic Dispersion Effect

The variable, ΔQ_i, in Eq. (8) is calculated without accounting for the hydrodynamic dispersion effect, D_s. If there were no hydrodynamic dispersion in the column, one pore volume would be sufficient to displace the water inside the column using the stock solution (pulse). That is, without D_s, the resultant BTC would be identical to the one shown in the Figure1a, where $C_r = 1.0$ at $P_r = 1.0$. In this case, the convective flow would be the only means by which the tracer was transported. However, D_s is known to make contributions to solute transport that vary depending on the characteristics of the porous media. Therefore, in the presence of D_s, more than one pore volume of pulse would be needed to displace one pore volume of water inside the column. Eq. (9) was proposed to account for the hydrodynamic dispersion effect on the transport of the tracer:

$$\Delta Q_{ci} = \frac{\Delta Q_i}{P_{r(Cr=1.0)}}, \qquad (9)$$

where, ΔQ_{ci} is the volume of effluent corresponding to convective flow and $P_{r(Cr=1.0)}$ is the dimensionless pore volume of effluent collected at $C_r = 1$. Finally, combining Eq. (8) with Eq. (9) yields Eq. (10);

$$K(C_{ri}) = \frac{\Delta Q_{ci}}{\frac{\Delta Q_{ci}}{\Delta P_i x P_0} t_i}. \qquad (10)$$

Eq (10) can be used to quantify the distribution of water flow rate using BTCs of nonreactive chemicals such as chloride and bromide.

2.3. Approximating Hydraulic Conductivity for a Specified Mobile Water Content, θ$_m$

The hydraulic conductivity at a specified soil mobile water content, θ_m (or matric head corresponding to the θ_m), is the function of all of the water filled effective pores. Therefore, the conductivity of the system for θ_m can be calculated as a cumulative function of Eq. (10) as follows:

$$K(\theta_{mi}) = \sum_{i=1}^{n} K(C_r)_i. \qquad (11)$$

where, $i=1$ corresponds to the hydraulic conductivity, $K(C_r)$, corresponding to the narrowest effective pore class in the system (calculated against a dimensionless concentration of 1.0 ($C_r = C/C_0 = 1.0$), and n corresponds to any prescribed value for θ_{mi}, which can be calculated as;

$$\theta_{m_i}(\Delta Q) = \sum_{i=1}^{n} \Delta Q_i. \qquad (12)$$

The variable $K(\theta_m)$ calculated by Eq. (11) can be interrelated to the matric pressure of mobile water by solving Eq.(2) and then Eq. (13):

$$h = \frac{2\sigma}{r}, \qquad (13)$$

where r (L) is the radius of the pore, and σ (FL^{-1}) is the surface tension of the soil water.

3. MATERIAL AND METHODS

The theory and methodology proposed in the theoretical section were applied to experimental breakthrough curves (BTCs) of chloride obtained using sand columns (30 cm length and 8.0 cm id) repacked with well-sorted washed sand grains. These sand columns were preferred to minimize the interactions between the chloride and the porous medium.

The sand columns were packed with sand screened sand with sieves with mesh sizes of 2, 1, 0.50 and 0.25

mm. To achieve an adequate packing, the bottom of the columns was gently tapped on the laboratory bench during packing.

3.1. Miscible Displacement Tests

Prior to conducting the miscible displacement experiment, both ends of the sand column were supported with a fabric. The core was then gradually saturated with 0.01 M KBr solution from the bottom of the column (van Genuchten and Wierenga, 1977). Upon saturation, the core was positioned on an upright stand, after which the inlet at the top of the column was connected to a disc infiltrometer with a base of 8 cm id (Figure 2).

After steady state flow was established under zero tension, approximately 6.0 pore volumes of tracer solution of 0.05 $CaCl_2$ in 0.01 M KBr solution were introduced into the column under zero tension using a disc infiltrometer. The effluent was then collected by a fraction collector and analyzed for chloride with a chloride specific electrode.

Following the miscible displacement tests, the sand column was removed and placed in an oven with a constant temperature of 105 °C to determine the bulk density and total porosity *f*. The total porosity was calculated by;

$$f = 1 - \frac{D_b}{D_p}, \qquad (14)$$

where, D_b is the bulk density (ML^{-3}) of the column and D_p is the density of particles (ML^{-3}), which was assumed to be 2.65 Mgm^{-3}. The saturated water content of the column was deemed to be equal to the volume of pores in the oven dried sand column.

Dimensionless concentrations of chloride were calculated by dividing the concentration of chloride in the effluent, measured with a chloride sensitive electrode, by the concentration of the stock solution measured using the same electrode.

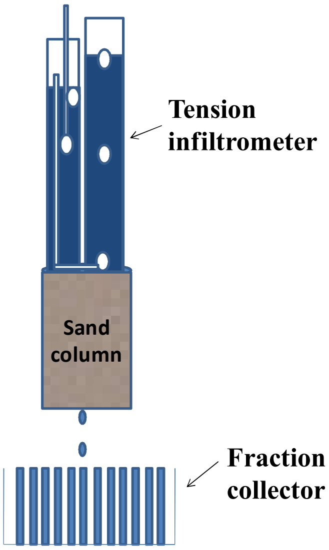

Figure 2. Apparatus used to conduct miscible displacement tests

3.2. Calculation of K(C_r)

Initial and boundary conditions:

Initial conditions: $t=0$, $C = 0$ and $t = t_s>0$, $C>0$ at the inlet of the column.

$C=0$, $V=0$ and $C>0$, $V>0$ at the outlet of the column

Boundary conditions: $t=t_{max}$, $P_r=P_{rmax}$, $C_r = 1.0$.

The following step-by-step procedure was applied using the above specified initial and boundary conditions:

1. Experimental BTCs for chloride were obtained by plotting the dimensionless concentration of chloride, C_r, against the dimensionless volume of effluent collected, P_r ($P_r = V/P_0$, where V is the cumulative volume of effluent collected and P_0 is the volume of water held in the saturated column, and $C_r = C/C_0$, where C is the concentration of chloride in the outlet and C_0 is the concentration in the inlet).
2. The property ΔP in Eq. (7) was calculated by multiplying P_r by its counterpart, C_r.
3. The value for P_0 was calculated by multiplying f in Eq. (14) by 100 cm^3 (the volume for each sand column), after which the values for ΔQ in Eq. (5) were calculated.
4. The value for ΔQ obtained during stage 4 above was divided by P_{rmax} (the value for P_r at Cr=1.0) to account for the hydrodynamic dispersion effect. This gave the value for ΔQ_c in Eq. (9).
5. The value of ΔQ_{ci} was divided by the corresponding value for P_{ri} (the value of P_r calculated in step i), which gave the value for $(\Delta A/A)_i$ in Eq. (10).
6. The value for the cumulative time elapsed (t) was determined as t_i-t_s, where t_i is the cumulative time elapsed for step i and t_s is the time (starting time) at which the first pulse infiltrated the column.
7. The values calculated for ΔQ_c, t, and ΔP were used in Eq. (10) to calculate K_i against the corresponding relative concentration, C_{ri}.
8. The calculations were repeated for about 30 points in each BTC to cover the range of C_r from $C_r=C_{rmin}$ (where C_{rmin} is the C_r at the first breakthrough of tracer) to C_r = 1.0. The calculations were conducted using a spreadsheet program prepared in MS-Excel.

3.3. Calculation of $K(\theta_m)$ by $K(C_r)$

The values of $K(C_r)$ were approximated by Eq. (11) for hydraulic conductivity against the mobile water content θ_{mi}, which was calculated by Eq. (12). For example, to calculate K_s ($K(\theta_m)$ at saturated water content) all of the $K(C_r)$-values were summed.

4. RESULTS AND DISCUSSION

The characteristics of the sand columns used to determine the miscible displacement of chloride are given in Table 1. As expected, the lowest bulk density D_b occurred when the particle size was smallest. The pore water velocity, ν (cm s^{-1}), decreased gradually as the particle-size of the sand in the columns decreased.

Table 1. Properties of repacked sand columns used in the miscible displacement tests. Each column has 30 cm length and 8 cm id.

Column ID	PS mm	D_b $grcm^{-3}$	f	K cms^{-1}	θ_s cm^3cm^{-3}	P_o cm^3
a	2-1	1.60	0.39	0.46	0.39	588.1
b	1-0.5	1.67	0.37	0.03	0.37	557.9
c	0.50-0.25	1.59	0.40	0.0073	0.40	603.2
d	<0.25	1.56	0.41	0.0064	0.41	618.3

PS: particle size, D_b: bulk density, f: total porosity, K: hydraulic conductivity, θ_s: volumetric water content at saturation, P_o: pore volume at saturation

The breakthrough curves of chloride for the sand columns are presented in Figure 3. Columns packed with different sized sand materials yielded different shaped BTCs. In general, the BTCs gradually shifted right in response to decreasing pore water velocity in response to the lower mean particle-size of the sand used to pack the columns. This shift was attributed to the smaller particles being arranged more closely, which resulted in stagnant regions that harbored larger amounts of Cl that was not readily displaced. Nielsen and Biggar (1961) attributed a right shift to soil texture and aggregation, with sand having the least amount of water not readily displaced and clays having the greatest amount of water that was not easily displaced.

The $K(\theta_m)$ was calculated from BTCs seen in Figure 3 and the results were shown in Figure 4. A sharp decrease in K versus θ_m is noticeable at the beginning for all the cases. Expectedly, the change in K against θ_m decreased more slowly after then.

The validity of the calculations was assessed, comparing saturated hydraulic conductivity measured K_{sm} with that calculated K_{sc} (Figure 5). As Figure 5 shows, the model over predicted for the column d (the column packed with <0.25 mm particle size, see Table 1). The correlation analysis between measured and calculated values for saturated hydraulic conductivity resulted in a correlation coefficient (r) of 0.91. This suggested that, in overall, the model developed proved to be useful at least in the experimental conditions set in this study. More data are needed to evaluate model in diverse porous media such as soils.

Number of studies conducted to evaluate the relationship of the breakthrough of water and/or chemicals to flow characteristics in porous media is limited. German and Beven (1981) used the Hagen-Poiseuille equation to describe macropore flow, and Radulovic et al. (1989) applied the same equation to evaluate soil macropore distribution from the water breakthrough curves. However, neither of these studies addressed the full range of effective pore-size distribution in soils. Rather, they considered only the macropore segment of the pore-size distribution range. Water flow in soils depends primarily on pore geometry and pore-size distribution, which are controlled by soil structure and soil texture. However, it is quite difficult to quantify the relationship between soil structure and water and solute transport in soils (Deeks et al., 1999). The theory and applications developed here suggest several directions for future research efforts. The development and application of laboratory techniques for the measurement of effective pore-size distribution together with the convective flow of water in soils with a variety of structures may generate a significant breakthrough in understanding water and chemical transport in structured soils.

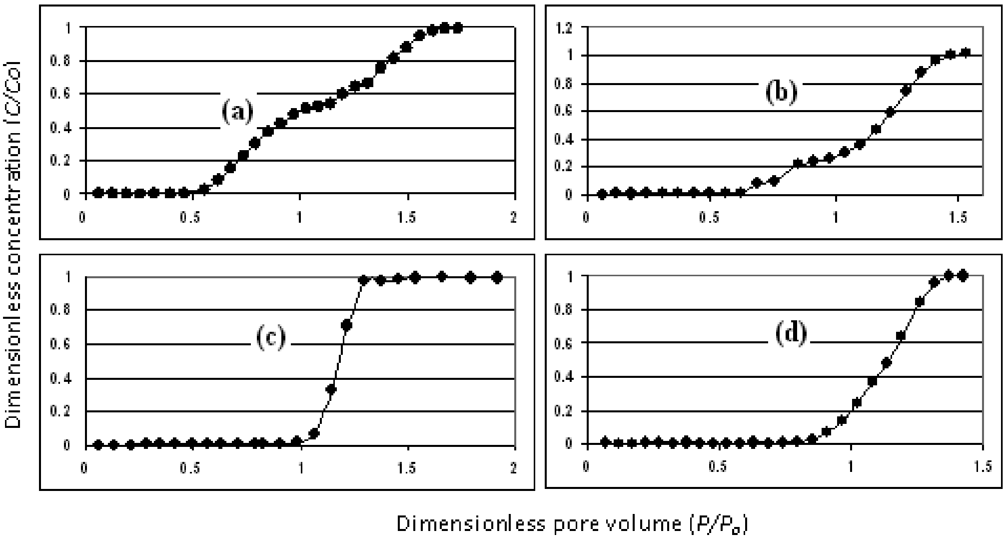

Figure 3. Breakthrough curves of chloride in columns prepared with uniform sand with particle size of a) 2-1, b) 1-0.5, c) 0.50-0.25, and d) <0.25 mm. See Table 1 for details of the columns

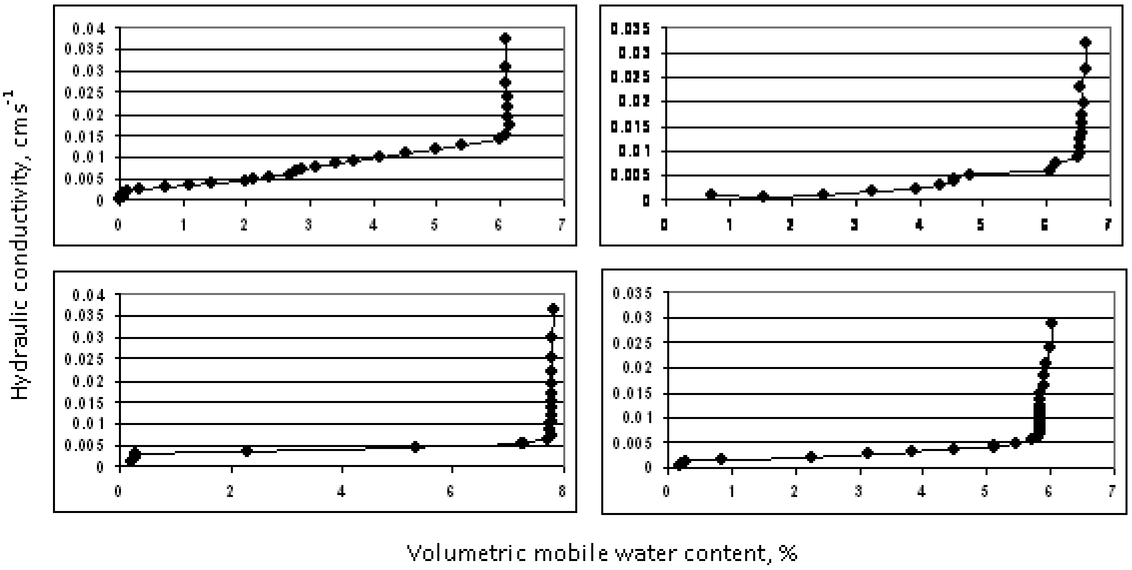

Figure 4. Hydraulic conductivity of the columns packed with uniform sand of particle size a) 2-1 mm, b) 1-0.50 mm, c) 0.50-0.25 mm, and d) <0.25 mm.

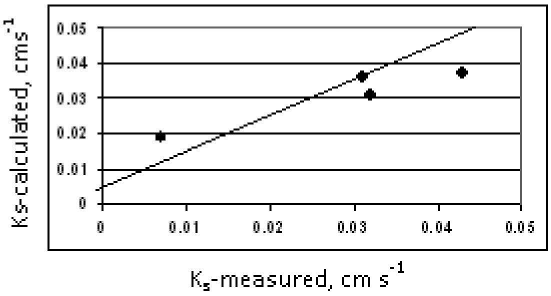

Figure 5. Relationship between measured and calculated values of hydraulic conductivity calculated with BTCs given in Figure 3. The diagonal represents the 1:1 line

5. CONCLUSION

Water flow was modeled in relatively large sand columns (30 cm long and 8 cm wide) packed with washed sands of different particle size. Darcy's equation was combined with the Pouisuille equation to approximate the hydraulic conductivity as a function of mobile water content calculated from breakthrough curves of Cl. The approximated results for the saturated water flow were then compared with measured K_s-values and found to be highly correlated ($r=0.91$, $P<0.01$) at all sand size-distributions evaluated. These findings demonstrated the validity of the method developed here for modeling hydraulic conductivity under saturated conditions in.

The theory and model developed in this paper differ from conventional models of water flow, which are based on the relationship of water content to water potential in soils. The model developed in this study is based on the amount of mobile water required to transport a known amount of tracer within a known amount of time. As expected, the particle size of repacked sand and the mobile water content of the columns were related. The theories proposed and the procedures developed in this study worked well in repacked sand columns. However, further research is needed to validate the calculations using intact and repacked soil columns.

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APPENDIX A

List of Symbols

A	Cross-sectional area of the column (L^2)
C	Concentration of the tracer in the discharged effluent (ML^3)
C_0	Concentration of the tracer in the stock solution (ML^3)
C_r	Relative concentration (C/C$_0$, dimensionless)
C_{rmin}	The minimum value for C_r
D_s	Hydrodynamic dispersion (L^{2}T^{-1})
D_b	Bulk density (ML^{-3})
D_p	Particle density (ML^{-3})
f	Porosity (dimensionless)
g	Acceleration due to gravity (L T^{-2})
H	Soil water head (L)
h	Soil water pressure/matric head (L)
K	Hydraulic conductivity (LT^{-1})
K_s	Saturated hydraulic conductivity (LT^{-1})
M	Concentration of tracer (ML^3)
L	Length (L)
P_0	Pore volume (L^3)
P_r	Relative pore volume (V/P$_0$, dimensionless)
P_{rmax}	Relative pore volume against C_r=1
Q	Discharge rate in the Poiseuille equation (L^3 T^{-1})
Q_{ci}	Volume of effluent corresponding to convective flow (L^3)
q	Discharge rate in Darcy's Equation (LT^{-1})
r	Radius (L)
t	Time (T)
t$_s$	Time at which the first pulse was introduced to the column (T).
t_{max}	Time (T) at C_r=1
V	Cumulative volume of the effluent collected (L^3)
z	Gravitation head (L)
η	Coefficient of viscosity (ML^{-3}T^{-1})
θ	Water content (L^{3}L^{-3})
θ_m	Mobile water content (L^{3}L^{-3})
θ_{mc}	Mobile water content contributing to convective flow (L^{3}L^{-3})
ρ_w	Density of water (ML^{-3})
σ	Surface tension of soil water (FL^{-1})
ν	Pore water velocity (LT^{-1})